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**(DURIP 10) HIGH-SPEED INTENSIFIED IMAGING SYSTEM FOR STUDIES OF MIXING AND COMBUSTION
IN SUPERSONIC FLOWS AND HYDROCARBON-FLAME STRUCTURE MEASUREMENTS AT ELEVATED
PRESSURES**

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**HIGH SPEED INTENSIFIED IMAGING SYSTEM FOR MIXING AND
COMBUSTION IN SUPERSONIC FLOWS AND HYDROCARBON-
FLAME STRUCTURE MEASUREMENTS AT ELEVATED
PRESSURES**

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Air Force Office of Scientific Research

DURIP Grant FA9550-10-1-0553

Final Technical Report

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Updated to 14 August 2014

Abstract

This report summarizes the acquisition and development of equipment, instrumentation, software, and their networking to augment optical diagnostics employed in supersonic reacting and non-reacting flow experiments. A high-speed camera system and image intensifier were acquired and integrated into the computer-controlled data-acquisition system of the Supersonic Shear-Layer facility at Caltech. Experiments to date have made use of this equipment, extending previous capabilities to high-speed schlieren quantitative flow visualization and image correlation velocimetry, with further experiments currently in progress.

Intensified camera and computer data-acquisition subsystem

The purpose of the effort and the associated development under the DURIP Grant No. FA9550-10-1-0553 was to acquire, adapt, and integrate a high-speed digital-imaging system to augment the diagnostics suite used in supersonic chemically reacting and non-reacting experiments, presently conducted as part of the research under the auspices of AFOSR Grant No. FA9550-12-1-0461. In addition to the acquisition of the new equipment, the development effort included a custom software development component, as well as testing and integration with the Supersonic Shear Layer (S3L) facility data-acquisition system and synchronization with other instrumentation.

A high-speed camera system and image intensifier were purchased to upgrade the quantitative flow visualization and diagnostic capabilities in these experiments. After a careful evaluation of several options and bids, the Cooke pco.dimax HD camera and Specialized Imaging SIL25GANG50 image intensifier were purchased. The pco.dimax HD camera is a 12-bit CMOS-based camera capable of over 1000 fps (frames per second) at its full resolution of 1920×1440 pixels. The image intensifier is a 25mm GenIII GaAs intensifier with a response time of less than $10 \mu\text{s}$ (10 microseconds).

As the title implies, the original proposal designated the equipment as dual-use to be employed both in supersonic-flow experiments as well as in high-pressure hydrocarbon-flame experiments. However, funding support for the latter was terminated and the equipment was eventually developed and used for the former.

The period of performance under this grant ended on 29 September 2011. However, delivery for the order for the image intensifier occurred several months later because of technical problems that were eventually addressed. Further, the extension of the capabilities of the pco.dimax HD camera occurred relatively recently under the auspices of AFOSR Grant No. FA9550-12-1-0461. These and other updates are documented in the discussion below.

High-speed camera subsystem

A Dell Precision Workstation 390 was purchased to control the camera and the intensifier. Windows 7 and the PCO (Cooke) CamWare software were installed on it. Interface software were developed and checked. The initial setup and testing was successful. The computer was also interfaced and networked with the S3L laboratory data-acquisition system and the larger Tyrvos data system network that supports this research.

We decided to use the pco.dimax HD camera for the schlieren system (see Fig. 1). The new camera has higher resolution than the Phantom V7.3 camera that was in use for the purpose (1920×1440 pixel resolution for the pco.dimax camera versus 800×600 pixels for the Phantom V7.3 camera). More importantly, the new camera could be upgraded to support a double-image mode with a short time-interval between image pairs. This was recently enabled with modified/updated firmware/software after interactions with the vendor and tested, as discussed below.

The new double-image capability allows us to record a pair of images separated by as little as $5 \mu\text{s}$, corresponding to a 200 kfps (thousands of frames per second). This enables image correlation velocimetry (ICV, Tokumaru & Dimotakis 1995) on a successive pair of schlieren images to measure the velocity field (e.g., Kegerise et al. 2000, Jonassen et al. 2006, Hargather et al. 2011).



Figure 1. Schlieren optical system showing the pco.dimax HD camera and the visible section of the lens assembly.

In order to take full advantage of the resolution of the new camera, we purchased a Tamron SP 90mm f/2.8 Di 1:1 AF macro lens with funds from this DURIP grant and 2 Samyang 85mm f/1.4 aspherical lenses with funds from the current AFOSR grant (No. FA9550-12-1-0461) to replace

the previous simple achromat lenses in the optical system (see Fig. 2). The latter were adequate before, but limited image quality with the new, higher-resolution camera. The new lenses improved resolution and reduced curvature of the image field of view.

A Dell Precision Workstation 390 was purchased to control the camera & intensifier. Windows 7 and the PCO (Cooke) CamWare software (see Fig. 3) were installed on it. Interface software were developed and checked. The initial setup and testing was successful.



Figure 2. Visible portion of current lens assembly

A high-speed pulsed LED was chosen for a light source and integrated with the rest of the system. The new LED light source provides much better stability and repeatability than the old spark-gap light source. A camera control program was developed using LabWindows CVI to control the LED light source and synchronize with the camera exposure signals. The new control program loads the timings from the master run setup file and stores them for use in subsequent data processing and analysis. Double-framed schlieren/shadowgraph images of supersonic flows with interframe times on the order of $5\mu\text{s}$ have been obtained (see Fig. 4).

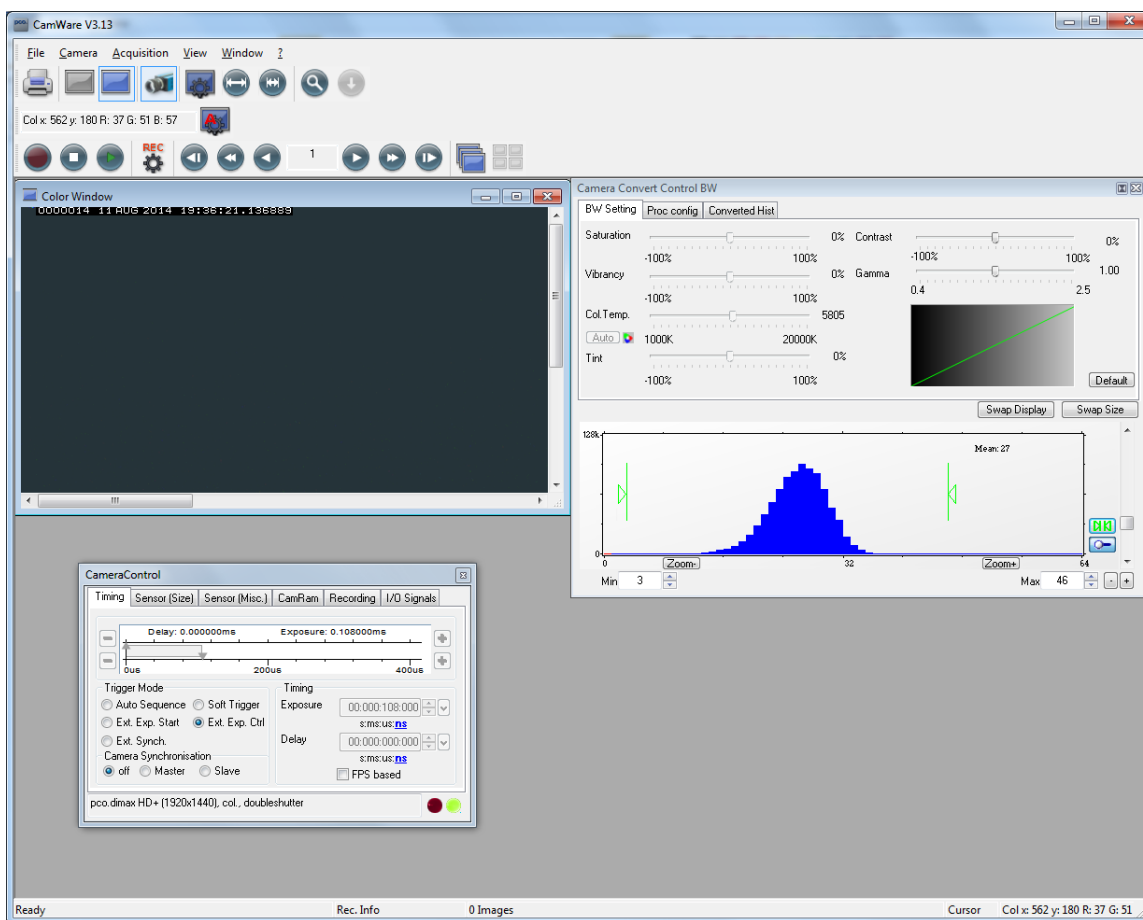


Figure 3. PCO CamWare camera control software screenshot.

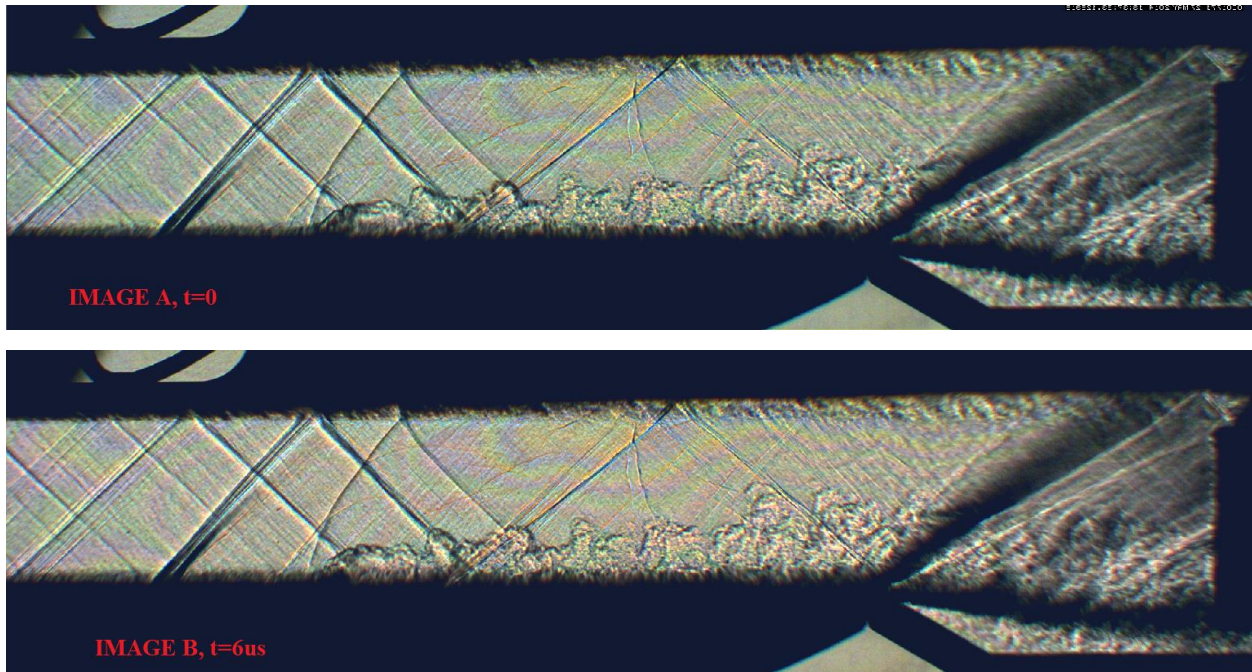


Figure 4. Double-pulsed schlieren images of supersonic flow with transverse jet injection. The displacement of flow features as they convect from the first image to the next is evident.

High-speed image intensifier

We have recently decided to pair our high-speed image intensifier (see Fig. 5) with the older Phantom V7.3 camera for simultaneous schlieren and chemiluminescence visualizations. This development is proceeding under support of AFOSR Grant No. FA9550-12-1-0461. The image intensifier is responsible for the limits to linearity and image resolution so the higher resolution and dynamic range of the pco.dimax HD camera is not as important for this application.



Figure 5. Image intensifier and control box.

We are currently designing and purchasing optics needed to support this capability.

To collect broadband ($\lambda > 505\text{nm}$) chemiluminescence, we plan to replace the current white LED with a blue LED and replace the mirror in front of the LED with a dichroic (longpass, 505nm) mirror. The dichroic mirror should reflect $>90\%$ of the LED light for the schlieren system towards the test section while transmitting most of the chemiluminescence ($\lambda > 505\text{nm}$) to a second mirror, and then to the image intensifier and Phantom V7.3 camera (see Fig. 6). This will allow for simultaneous schlieren and chemiluminescence visualization of reacting supersonic flows. The mirror arrangement for collecting CH^* chemiluminescence (emits at $\lambda_{\text{CH}^*} = 431.5\text{nm}$) will be slightly different: a white LED will be used with a shortpass (450 nm) dichroic mirror and a bandpass ($\Delta\lambda = 10\text{nm}$ at $\lambda = 430\text{ nm}$) filter at the intensifier. Most ($\lambda > 450\text{ nm}$) of the white light from the LED will be reflected towards the schlieren system, while allowing spectrum containing the excited methyl radical (CH^*) chemiluminescence to pass. This part of the effort is funded under the current AFOSR Grant No. FA9550-12-1-0461.

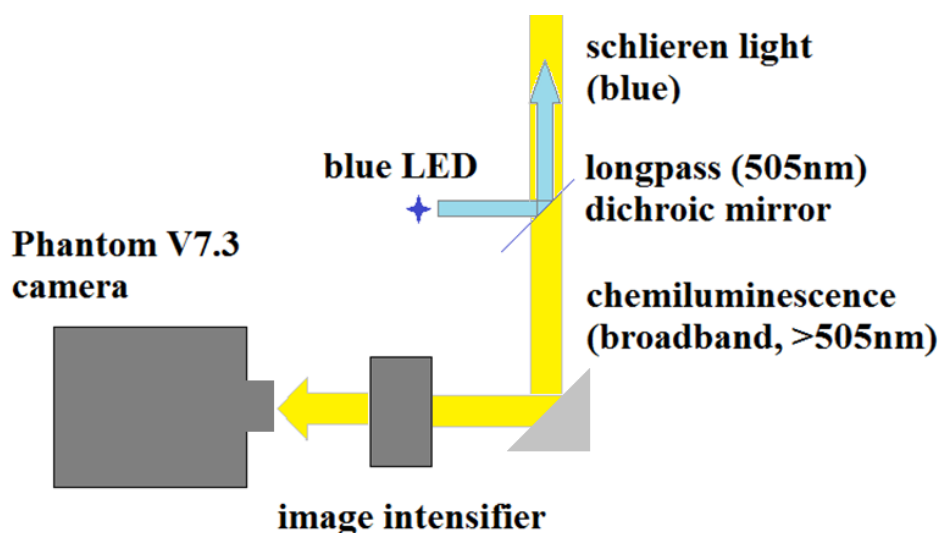


Figure 6. Broadband chemiluminescence system diagram.

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